PROJECT WHIRLWIND

(Device 24-x-3)

SUMMARY REPORT NO. 21

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MASSACHUSETTS INSTITUTE OF TECHNOLOGY

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FOREWORD

Project Whirlwind

Project Whirlwind at the Massachusetts Institute of Technology Servomechanisms Laboratory is sponsored by the Office of Naval Research under contract N5ori60. The objectives of the Project are the design and development of an electronic digital computer of large capacity and very high speed, and its application to problems in mathematics, science, engineering, simulation, and control. At the present time nearly all project resources are devoted to the design, construction, and testing of the computer.

The Whirlwind Computers

The Whirlwind computer will be of the high-speed electronic digital type, in which quantities are represented as discrete numbers, and complex problems are solved by the repeated use of fundamental arithmetic and logical (i.e., control or selection) operations. Computations are executed by fractional-microsecond pulses in electronic circuits, of which the principal ones are (1) the flip-flop, a circuit containing two vacuum tubes so connected that one tube or the other is conducting, but not both; (2) the gate or coincidence circuit; (3) the electrostatic storage tube, which uses an electron beam for storing digits as positive or negative charges on a storage surface.

Whirlwind I (WWI), now being built, may be regarded as a prototype from which other computers will be evolved. It will be useful both for a study of circuit techniques and for the study of digital computer applications and problems.

Whirlwind I uses numbers of 16 binary digits (equivalent to about 5 decimal digits). This length was selected to limit the machine to a practical size, but it will permit the computation of many simulation problems. Calculations requiring greater number length will be handled by the use of multiple-length numbers. Rapid-access electrostatic storage will have a capacity of 32,000 binary digits, sufficient for large classes of actual problems and for preliminary investigations in most fields of interest. The goal of 20,000 multiplications per second is higher than general scientific computation demands at the present state of the art, but is needed for control and simulation studies.

Reports

Quarterly reports are issued to maintain a supply of up-to-date information on the status of the Project. Detailed information on technical aspects of the Whirlwind program may be found in the R-, E-, and M-series reports and memorandums that are issued to cover the work as it progresses. Of these, the R-series are the most formal, the M-series the least. A list of the publications issued during the period covered by this Summary, together with instructions for obtaining copies of them, appears at the end as an appendix.

I. QUARTERLY REVIEW (AND ABSTRACT)

The installation during the final quarter of 1949 of equipment for automatic marginal checking by voltage variation has greatly accelerated the refining of the computer, because it permits more rapid circuit evaluation and trouble location. All of the system, including the arithmetic element, central control, and test storage, has been under test as an integrated unit. Electrostatic storage and Eastman film reader-recorders are being developed with specialized test control. Other terminal equipment, including punched paper tape and magnetic tape, remains to be designed or procured. We expect that film units and paper tape will be available to the computer as terminal equipment early in the summer; magnetic tape will follow as design time permits.

The electrostatic-storage prototype digit column was given further tests preceding a shutdown in December to permit installation of wiring for marginal checking of the storage system. We were able to cycle 16 × 16 spot arrays for error-free periods of an hour with a storage access time of 25 microseconds. These tests were made using the complete electrostatic storage control and deflection circuits.

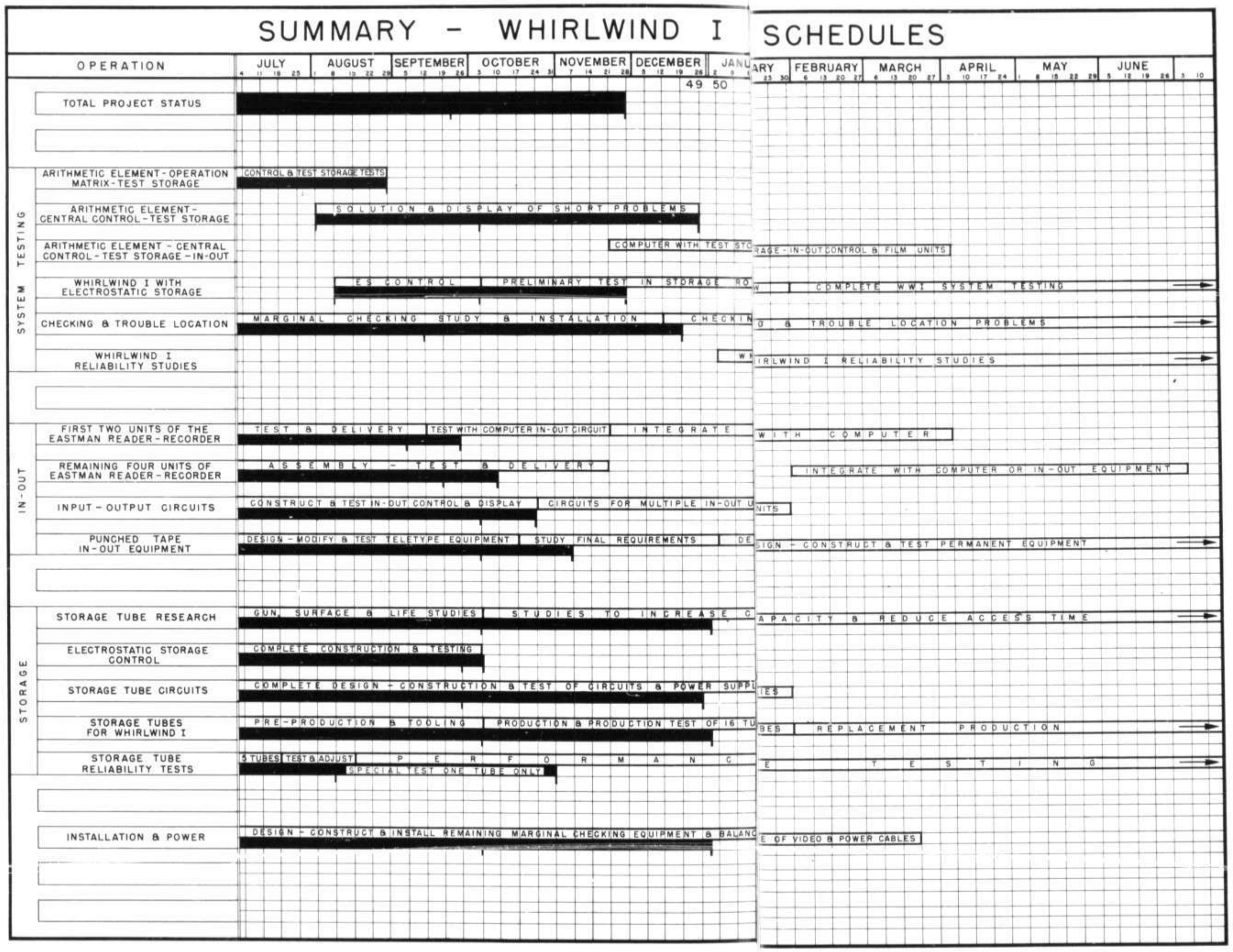
The first film reader-recorder unit has been tested both by itself and in conjunction with the computer input-output control and registers. More than the anticipated modifications have been required, so that this item is somewhat behind schedule. We feel, however, that progress is reasonably consistent with the development of other parts of the computer.

Reliability of the five-digit multiplier has been maintained. Seven random unexplained errors were recorded during this quarter, the same number as occurred during the period of July through September. Vacuum-tube life in the multiplier has been very satisfactory. We have found that a large proportion of 7AD7 and 7AK7 tubes may be expected to exceed 10,000 hours of useful life.

Vacuum-tube replacement in Whirlwind I continues at a low rate. During this quarter 40 out of 3500 tubes were replaced.

Storage tubes have been completed for the initial testing of electrostatic storage in Whirlwind I with 16 tubes having a capacity of 256 digits per tube. Production has started on tubes having a shorter throw, which give promise of higher-density storage. We have found that storage surfaces far outlive gun cathodes and we have successfully replaced the guns and reprocessed the tubes. Plans have been completed for simplifying the construction of storage tubes by putting both high-velocity and holding guns in one neck instead of in separate necks as in the past. Research toward decreasing spot size and improving cathodes has continued.

Several programs have been written and run on the computer for the solution of second-order differential equations. The computed results are displayed on an oscilloscope. As described in Section 6, the ability to rapidly change parameters makes some interesting mathematical results immediately obvious and suggests very useful applications for such displays.



LEGEND

JULY

Period of one month, comprising the total number of days in the month.

PROTOTYPE

Operation to be performed, and the estimated time allotted for its completion. Estimates made in January 1949.

Indicates extension of the work into next period.

Work done. The ratio of the length of the solid bar to the length of the open bar above it shows percentage of completion at the end of the month.

Date of the latest posting.

Summary line. Shows the overall status of the project.

2. SYSTEM ENGINEERING

2.1 TESTING AND INSTALLATION OF WWI

2.11 System Tests Using Marginal Checking

Much of the system testing in the last quarter has been on use of voltage variation equipment for marginal checking. For several months, equipment permitting manual variation of important d-c supply voltages has been available. Since November 30th, when the installation of automatic selection and variation equipment was completed, the capabilities of marginal checking have been greatly extended.

This equipment permits automatic variation of the voltage in some 300 d-c supply circuits, automatically selected in sequence. Since it is impractical to supply separate variation circuits to each tube of the computer, the circuits are allotted to groups of tubes. These groups are so chosen that troubles may be isolated by appropriate problem sequences.

Experience has shown that effective marginal checking requires the variation of the voltage on fewer circuits than was originally considered necessary, making possible the application of this checking method to the whole computer with only a few more voltage-variation circuits than were originally planned for the arithmetic element alone.

Some disturbance has been caused by transients on the power lines due to poor timing of the relay operation sequence on the voltage-variation panels (the relay shorting the variable-voltage bus must close before and open after the main-line relay opens and closes); contact bounce and chatter sometimes cause random transients during the switching period; and on heavily loaded circuits the sudden application of the full circuit current to the variable-voltage generator may cause transients. Therefore a "transient-block" was added to deactivate the computer (place it in the "push-button" condition) while the circuit switching is taking place.

A typical automatic marginal checking sequence is as follows:

a. The proper test problem is inserted in storage, and the computer is placed in operation (the problem being repeatedly solved at some arbitrary rate, perhaps every millisecond).
b. The number of the first circuit (flip-flop screen-voltage, for example) is dialed into the panel-selection equipment (a combination of a telephone crossbar switch, stepping relays, and various control relays).
c. The "manual-automatic" operation key is placed on "automatic", and the "start" key is pressed.
d. The computer is now automatically placed on push-button (clock stopped); the voltage-variation panel relays put the voltage-variation generator in series with the voltage feed to the screens of the tubes forming the zero side of the flip-flops in a pair of digits of the arithmetic element and test storage.
e. When all the relays have operated, the computer is automatically cleared and the test problem restarted. The motor-driven potentiometer feeding the field of the generator makes one revolution at a rate that has been previously set by the operator. During this revolution the output of the generator varies the line feeding the flip-flops above and below normal voltage, the amount of variation being determined by the setting of potentiometers in the particular voltage-variation circuit. When the output of the voltage-variation generator returns to zero, it signals both the computer and the voltage-variation circuit.
f. The computer is again switched to push-button, the voltage-variation circuit being used is returned to normal, the crossbar switch is indexed by one, the next circuit in the sequence is selected, and its relays operate.
g. This procedure continues until an error occurs or the operator stops it.

As explained in Summary Report 8, an error causes the voltage-variation cycle to stop, after which the operator proceeds to locate the trouble by an appropriate method.

All of this equipment is built, installed, and operating. Much can yet be learned about the most effective use of the marginal checking method. The whole system promises to be an even more useful tool in trouble location than was originally anticipated.

Marginal checking was installed to permit isolation and replacement of deteriorated components before they caused errors in computation. Thus it has been used in routine preventive maintenance and, in the initial stages of computer operation, as a design-check aid. Manual selection and variation of circuits was slow and cumbersome. Automatic variation, however, has permitted the rapid determination of just which circuits have low operating margins without the necessity of making detailed measurements on those with good margins.

Previous to the availability of automatic voltage variation, periodic manual variation was used to determine the dynamic balance of all flip-flop circuits. As described in Report E-317, the screen voltage of each tube of a flip-flop is varied separately, and the voltage deviation at which operation fails is recorded. For a good flip-flop, the deviations for both sides are equal and within certain

limits. Unbalance indicates trouble, and some additional tests show which component of the circuit has deteriorated. Tubes and crystal rectifiers are the most common failures in flip-flop circuits; the condition of these components is indicated directly from the test data. Success in anticipating failures has been good. As a result of these checks, machine errors have been in no case traced to faulty flip-flops.

The installation of automatic marginal checking has so accelerated the procedure that it has been possible to greatly extend the number of circuits which are given periodic preventive maintenance checks. In addition to flip-flops, gate tubes and many other circuits are now included.

Marginal checking techniques are not yet sufficiently developed to permit anticipation of all necessary component replacements, and there has inevitably been gradual deterioration of some components. Voltage variation has already greatly speeded up the location of these failures. It is particularly useful in finding components causing infrequent errors which would otherwise be very difficult to locate. An intermittent error can often be made steady by manual variation of voltage to the suspected circuit; location of the specific component at fault is then a simple matter.

One of the most valuable uses of marginal checking has been in verifying circuit design. For example, see the description of the shortcomings of the test-storage coupling system in Summary Report 20. A circuit simplification has resulted in a new system which now has adequate margins. The a-c coupling, which clamped the bottom of waveforms received via the matrix drivers to the grid bias level, caused small variations in waveform amplitude to appear at a very steep region of the transfer characteristics of the gate tubes. Thus small variations of suppressor-grid signal were highly amplified in terms of output-pulse amplitude. An a-c coupling system, common to many other WWI circuits, which clamped the top of suppressor waveforms was not applicable here. It was apparent that d-c coupling of the type recently installed in the control matrix was needed (2.132, Summary Report 20). A form of this circuit has been installed to provide a constant suppressor-grid signal under any condition of toggle-switch settings and over a wide range of circuit conditions. Test storage has performed very well in the two months since these changes were made.

2.12 Equipment and Wiring Installed

By the end of 1949 power wiring in WWI was more than 95 percent complete. During the last three months of the year all electrostatic storage wiring, including that for control and deflection equipment, was installed.

Shop production of the remaining portions of WWI progressed well. Most of the video cabling was finished. The 18 signal-plate driver panels for electrostatic storage digits were completed; 6 of the 8 required special storage-tube power supplies were built; over half of the 18 gun-driver panels were finished; 10 of the first 16 storage-tube mount boxes were received from the manufacturer, and wiring of the first one was completed; all sheet-metal and subassembly work on the storage-tube output gate panels was completed and final assembly was begun; and 12 of the first 16 storage-tube output r-f amplifiers were completed.

Shop construction of storage-tube circuits remains to be completed. Voltage-variation wiring for the Eastman reader-recorder equipment must be installed. Control wiring and equipment for the storage-tube power supplies have been designed, but must be built and installed. All of this work should be completed by March.

With the generous cooperation of the New England Telephone and Telegraph Company, a program of relay adjustment and maintenance was begun in November and is still continuing. All relays in the power distribution system are being cleaned and carefully adjusted to manufacturer's specifications. A representative of the Telephone Company spent several weeks with the Project, giving training to our technicians.

2.2 TEST OF STORAGE DIGIT PROTOTYPE SYSTEM

Electrostatic storage control and deflection were installed and given initial tests in the third quarter of 1949. It was then possible to check tube operation in the final location in the computer. The System Engineering Group has during the last quarter studied the operation of a storage tube in a prototype digit column in WWI with the electrostatic storage control and deflection generators. Successful operation for periods of about one hour was obtained. Work will continue as additional final computer circuits and storage tubes are installed.

Testing of both storage and the rest of WWI can be carried on simultaneously. Temporary power wiring was used; therefore no marginal checking of the storage control, the test equipment, or the digit column itself was available, and temporary power supplies were required to operate the storage-tube mount. Most of the testing consisted of cycling the information through a storage tube as is done in the reliability tester. See Summary Report No. 16, January 1949, for details.

2.21. Initial Operation Using Storage Tube ST77

An early model storage tube (ST77) was selected for initial operation of the digit prototype. Cycling tests of a 16 × 16 array were run over a period of weeks with continual improvement in operation. Runs of approximately an hour were made without error. An access time of approximately 25 microseconds was used for these tests.

The study revealed several weak points, which were corrected. Among these, the marginal stability and susceptibility to power-line noise of the decoders in the deflection units required some circuit redesign. Early in the testing of ST77, the cathode of the high-velocity gun was damaged, apparently because the control grid was accidentally driven positive with respect to the cathode. The beam current was greatly reduced, but was restored to a usable level by operating the filament at more than 6.3 volts.

Although cathode damage had not been encountered in the experimental test setups, it was decided to provide a protective circuit in the mount to prevent the grid from being driven positive with respect to the cathode. Otherwise, an unexpected disturbance might damage an entire bank or possibly even two banks of storage tubes while the computer was in operation. The mount circuit was changed so that a high impedance is now inserted in the storage-tube cathode as soon as the control grid calls for more than a predetermined amount of cathode current. Thus the high-velocity gun is essentially a cathode follower with zero cathode impedance up to the desired beam current and an extremely large cathode impedance above this beam current. This not only provides protection for the cathode against grid overloads, but also increases operation stability by stabilizing the cathode current so that no decrease results from decay of emission with time. A new prototype mount was constructed to these specifications and the digit prototype put back into operation.

2.22 Future Plans

The entire computer was shut down in December for the installation of video cables and d-c wiring. At the same time marginal checking facilities were added to the storage. The test control for the storage will be moved to the control room from its present position near the storage control. Remote TV and display scopes will be added with push button selection of the desired digit column.

Early in the next quarter a digit prototype will be installed using production panels, mount, and storage tube. This column will be checked out and additional columns added as fast as possible. The entire row is scheduled for installation before the end of the next quarter. The provision of marginal checking should greatly assist in bringing the operation of the circuits to the desired state of reliability.

3. CIRCUITS AND COMPONENTS

3.1 FIVE-DIGIT MULTIPLIER

The five-digit multiplier, a prototype of the WWI arithmetic element, has been operating on an extended life test since April 1, 1949. The system is arranged to perform the multiplication of 31×31 at a cyclic rate of about 15,000 times per second. Automatic checking circuits are incorporated in the system to verify each solution and to record on relay-type counters if an incorrect result is obtained.

The primary purpose of the test is to determine what degree of reliability can be expected in a system containing electronic circuits such as are used in the WWI computer. The test also is giving valuable data on the effectiveness of marginal-checking techniques and on the life of vacuum tubes and other circuit components.

Test results for the period from April through September have been reported in Summary Reports 19 and 20. These showed that considerable improvement in reliability was obtained as a result of work done during the first three months of the test and of maintenance performed during a two-week shutdown the first of July.

In general, multiplier operation over the last quarter has been as satisfactory as that realized in the period from July through September. A chart of multiplier performance is reproduced on page 12. A total of seven random error counts were recorded, the same number of such counts as for the previous quarter. These seven error counts occurred during the month of October.

In addition to the random errors there were four periods in which incorrect operation was obtained for extended intervals of time. The first of these periods resulted from the sudden failure of a gate tube in the test-equipment circuits which supply control pulses to the system.

Two of the other system failures were attributable to a faulty bias supply generator. Installation of new brushes on this machine after the first of these failures corrected the situation for only about a week; then it was found necessary to turn down the commutator. The four motor-generator sets which are used to supply d-c power to the multiplier were installed a considerable length of time before the current life test was begun, and were selected from used stock without special regard for reliability. It has been found that the bias generator in particular has required more maintenance than normally would be expected for such a machine.

The fourth system failure was caused by a change in control-circuit cabling which resulted in marginal operation. This change was made for test purposes, and the proper cabling was not restored at the end of the test.

Component replacements during the last quarter were 18 vacuum tubes and 7 crystal diodes. A total of 350 tubes and 900 crystals are used in the equipment. All these replacements were made as a result of data obtained from routine marginal checking which is carried out each working day during the life run. This checking requires an average of about 30 minutes per day.

3.2 VACUUM TUBE LIFE

3.21 Vacuum-Tube Life in WWI

Perhaps the most significant information on vacuum-tube life in WWI is the low failure rate. This may be attributed in large measure to the care taken in preparation of these tubes for use in WWI. Favorable heater operating conditions have undoubtedly contributed to the fact that only one heater has burned out to date. As shown in the table on page 13, 40 tubes have been replaced in the last quarter. Eleven 7AD7 tubes showed changed characteristics at between two and three thousand hours. Of these 11 tubes, two had shorts as well as changed characteristics, and were not pulse tested. Of the 9 tubes pulse tested, 7 had developed cathode interface resistances. The value of the resistance was in general about 30 ohms, but one tube had an equivalent resistance of 50 ohms. Only two of those tested had no interface resistance. Seven of the tubes tested were of the B8B production lot; this is the lot of 7AD7 tubes which was originally found to be faulty in the five-digit multiplier. Six of the tubes of the B8B lot were found to have interface resistances.

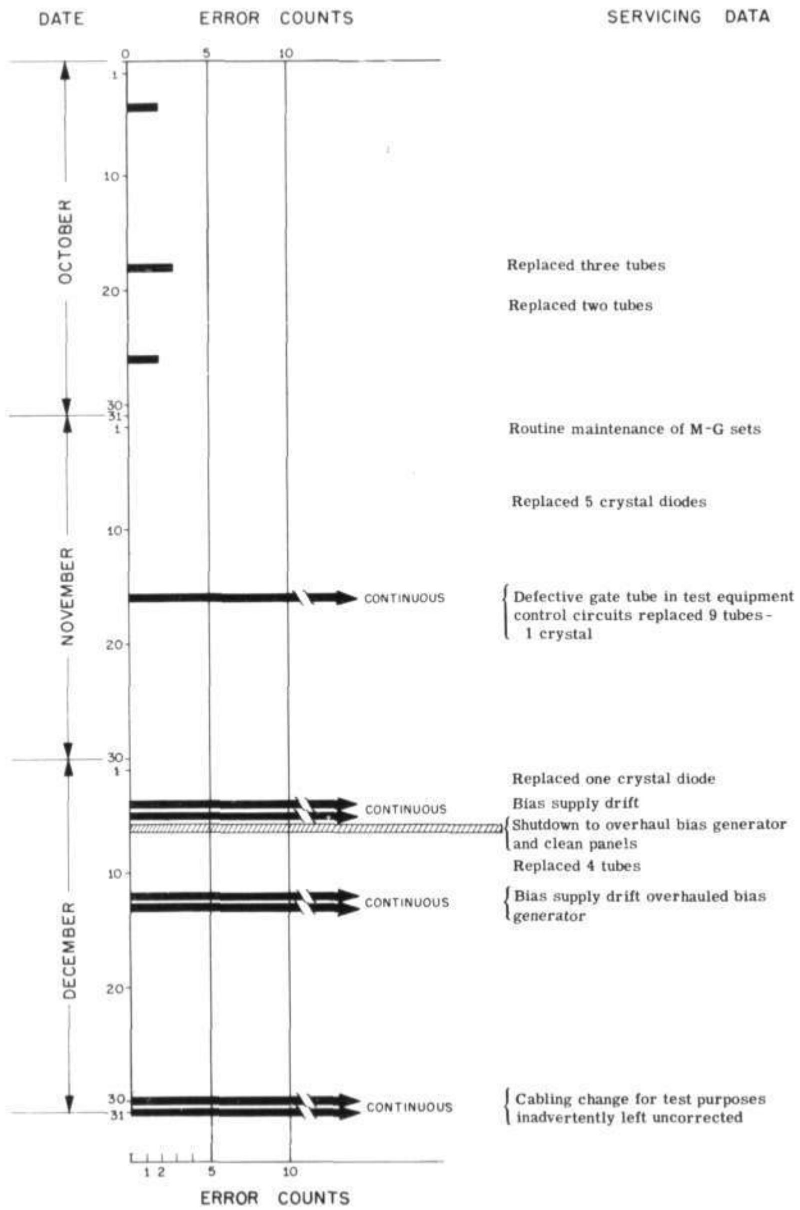
3.22 Vacuum-Tube Life in the Five-Digit Multiplier

The five-digit multiplier has proven to be a valuable testing ground for tubes, circuits, and techniques. From the data obtained, a large proportion of 7AD7 and 7AK7 tubes may be expected to exceed 10,000 hours of useful life. This is very favorable from the point of view of down-time necessary to replace vacuum tubes.

Vacuum-tube life data have also shown that expected life of 6AS6 and 6AG7 tubes lies between five and ten thousand hours. Pulse plate currents required of the 6AS6 tubes in the five-digit multiplier are considerably in excess of rating for steady-state current. The most common failure of 6AS6 tubes is low plate current caused by low emission. No other tube types have shown this difficulty.

Operation of the multiplier was not interrupted at the end of the third quarter for a periodic test of the tubes in the equipment. Consequently most of the tubes have been in use for a period of six months

FIVE-DIGIT MULTIPLIER PERFORMANCE



TUBE FAILURES IN WWI

October 1 – December 31, 1949

Type	Total in Service	Hours at Failure	Reason for Failure: Change in Characteristics	Mechanical	Burn-Out	Gassy
7AK7	1330	0-100				
		100-500				
		500-1000				
		1000-2000	1			
		2000-3000				
7AD7	1462	0-100				
		100-500	1	1		
		500-1000	4	2*		1
		1000-2000	3	7		
		2000-3000	11	2		
3E29	92	0-100				
		100-500		1		
		500-1000				
		1000-2000	1			
		2000-3000				
6SN7	391	0-100				
		100-500	1			
		500-1000				
		1000-2000				
		2000-3000	1	1		
6Y6	204	0-100				
		100-500				
		500-1000				
		1000-2000				1
		2000-3000				
2C51	14**	0-100				
		100-500	1			
		500-1000				
		1000-2000				
		2000-3000				
6L6	37		No Failures			
6V6	15		No Failures			
2D21	20		No Failures			
6AN5	4		No Failures			

* One of these failures occurred in a panel which has since been eliminated.

** At the start of this period there were 44 2C51's in service, but circuit modifications eliminated 30 tubes. The failure occurred in a section eliminated.

or about 4000 hours since their last test. Undoubtedly many of these have experienced some deterioration, but it is felt that reliance should be placed on marginal checking to indicate when a tube is approaching the end of its life. The failure point for a given tube, therefore, is determined by the particular circuit in which it is used. Consequently some tubes which would have failed in flip-flop applications because of cathode-interface type of deterioration still function satisfactorily as buffer amplifiers passing 0.1-microsecond pulses.

3.23 Vacuum-Tube Life Tests

Additional data have been obtained on all tubes reported in Summary Report 20. Information is available on 6AN5 tubes at 3000 and 4000 hours, on 6AG7 tubes at 3000 hours, and on 7AD7 tubes at 6000 hours. Tests of static currents and interface measurements were made; in general most changes since Summary Report 20 are small.

In the 6AG7 tubes, only those with RCA N34A "active" cathode sleeve alloy (Driver-Harris 799) have shown major changes. These tubes now have average interface resistances ranging from 3 ohms in a group used as normally-on tubes to 32 ohms in a group used as normally-off tubes. The plate currents on static test are also low, ranging from about 80 percent to less than 50 percent of the initial plate current. In the cases of the other two cathode alloys under test, RCA N81 passive (Driver-Harris 499) and RCA N109 (International 220), plate currents are in general about 90 percent of the initial value, and no interface resistances have been found.

In the 6AN5 tubes, plate currents have remained at 90 percent or more of initial value. In many cases the plate currents at 4000 hours are greater than those at zero hours. No interface resistance formation has been found. However, one tube on static test and one tube on flip-flop test were retired at 3000 hours because of drastic changes in their cutoff characteristics. It has been found that 6AN5 tubes tend to develop gas and primary grid emission if operated normally-off, but the currents resulting are usually less than 1 microampere.

The special 7AD7 tubes mentioned in Summary Report 19 and Summary Report 20 have now been retired after 6000 hours of operation in order to free space for other life tests. These tubes have yielded a certain amount of useful information, but have not answered the original question of which factors are responsible for the difference in performance between the L7P and B8B lots of 7AD7 tubes. The changes in plate material and bulb coating which were made between these two lots seem not to be responsible for interface formation.

Contrary to the report in Summary Report 20, of the specially constructed 7AD7 tubes only those with 599 alloy cathode sleeves have shown any interface resistance formation. Spectrographic analysis of the cathode sleeves of two tubes which had been in the 599 group and two tubes which had been in the 499 group showed that these four tubes had been interchanged. This analysis was performed by Mr. James Cardell of Raytheon Manufacturing Company. Thus, all 10 tubes with 599 alloy cathode sleeves showed interface formation, while none of the 10 tubes with 499 alloy cathode sleeves showed any interface formation. This is as expected, since it is believed that silicon is responsible for the formation of cathode interface resistance, and 599 alloy contains 0.05 to 0.15 percent silicon, while 499 alloy contains less than 0.01 percent.

It should be mentioned here that some factor other than the cathode sleeve appears to be responsible for supplying silicon to form cathode interface resistance in production 7AD7 tubes, since interfaces formed in one production lot but not in another lot although both used the same alloy. This alloy is Sommers A, which is relatively free of silicon, having about 0.03 percent silicon or less.

A lot of 10 production 7AD7 tubes has been carried along with the special 7AD7 tubes mentioned above. These tubes are of lot F8B, which is used widely in WWI. Of these 10 tubes, only one of the five operated normally-off has shown interface formation; it now has an interface of over 80 ohms. None of the five normally-on tubes has shown interface formation. None of a group of 10 7AD7 tubes of F8B production operated with 5 volts on the heaters and with plate current biased off have shown any measurable interface resistance at 5100 hours.

These tests have produced few definite positive results. They have, however, shown that long and extensive life tests are required to produce changes in tubes of high quality. They have also shown that, while factors other than the cathode sleeve material may be responsible for interface formation in some cases, the use of active cathode sleeve material, Driver-Harris 599 or 700 alloys, will almost certainly result in the formation of cathode interfaces which will interfere with the operation of high-transconductance vacuum tubes used in computer circuits.

3.3 COMPONENT REPLACEMENT IN WWI

The table of component replacement on page 15 shows that, with the exception of tubes and crystals, only 11 components have been replaced in WWI during the last three months. Most of the 37 crystal rectifiers which were replaced had not initially been tested to the rigorous no-drift standard now in effect. The need for replacement was in most cases indicated by marginal checking.

FAILURES OF COMPONENTS IN WWI

October 1, 1949 – December 31, 1949

Component	Type	Total in Service	No. of Failures	Hours of Operation	Comments
Capacitor	0.001 mfd	2900	1	1547	(Mica) Coupling capacitor – poor pig-tail connections caused intermittent operation.
	0.1 mfd	300	2	1625	(Paper – tubular oil filled). Leaked oil.
Choke	50 μh	1400	1	2183	Open circuited.
Connector	UG-290/U	6700	1	1644	Broken insulation.
Crystal Rectifier	D-357	6400	5	100-500	Clamping crystals: 4, excessive drift; the other, low back resistance.
			2	500-1000	Reset crystals – excessive drift.
			1	1000-1500	Mixing crystal – low back resistance and drift.
			2	1500-2000	Grid crystals – excessive drift.
			1	2000-2500	Grid crystals – excessive drift.
	D-358	3100	9	100-500	8 clamping crystals: 4, low back resistance and drift; 4, excessive drift. One mixing crystal, low back resistance and drift.
			7	500-1000	Clamping crystals; excessive drift.
			5	1000-1500	Clamping crystals; excessive drift.
			4	1500-2000	Clamping crystals: 2, excessive drift; 2, low back resistance.
			1	2000-2500	Matrix crystal; excessive drift and low back resistance.
Pulse Transformer	1:1	550	1	434	Open primary.
	3:1	2500	1	259	Open secondary.
Relay	8HXX	150	1	1830	(Struthers - Dunn) – Open coil.
Resistor Carbon	220 ohms 1 watt	9000	1	1100	Burned out.
			1	1580	Burned out.
Wire-Wound	5000 ohms 8 watts	650	1	1730	Opened.

3.4 DECOUPLING NETWORKS FOR COMPUTER CIRCUITS

Suitable decoupling networks present a design problem common to most computer applications. Computer circuits often require large current steps as well as high pulse currents to be drawn from power supplies. Decoupling networks are needed at each stage to prevent interaction through power-supply and feeder-line impedances. (A preliminary discussion appeared in Summary Report 4.) Simple resistance-capacitance networks provide effective isolation under pulse operation, but the series resistance of these networks causes poor voltage regulation when large current steps are required. Inductance-capacitance networks have less effect on voltage regulation; however, these are usable only if their resonant frequencies are much lower than the lowest frequency component of the signal.

In WWI, decoupling is provided by two types of networks. In the typical pulse circuit, in which the average current is no more than a few milliamperes, a resistance-capacitance section of 220 ohms and 0.01 microfarad in each supply-voltage line to every stage provides effective isolation of pulse currents between stages within the racks. Voltage regulation is not impaired, because of the small average currents. In other circuits subject to current steps as high as 75 milliamperes, the series resistance is reduced to 22 ohms or less, and decoupling efficiency is maintained by increasing the capacitance. Because of the lowered resistance, this may be done without sacrificing the low time constant.

To prevent coupling through feeder-line impedances between racks, an inductance-capacitance section has been placed in d-c lines at the point where they enter each rack. These networks, each consisting of a 1-millihenry inductor and a 1-microfarad capacitor, have a resonant frequency of less than 5 kilocycles per second and produce little d-c voltage drop. This decoupling system provides excellent decoupling for high pulse currents and has performed well except when it can be shock-excited to give damped oscillation.

Damped oscillations of rack decoupling circuits were found to cause occasional low operating margins in certain problems. Routine marginal checking by voltage variation showed that for these problems the gate tubes were abnormally sensitive to raised screen voltage. Sudden changes of plate current when the gate tubes were switched between conducting and non-conducting states produced shock excitation of the L-C decoupling networks. A ripple of 5 to 8 volts on the plate supply line resulted. While WWI circuits are normally insensitive to supply voltage changes of that magnitude, grid clamp action, which was exaggerated when the screen-grid voltage was raised in measuring margins, caused faulty operation. The oscillation appeared only when the gate tubes remained in first one state and then the other for long periods of several hundred microseconds. In most computation the gate tubes are switched at much shorter intervals, but the period is determined by the problem which the computer is solving.

The condition was corrected by feeding the plates of the gate tubes through a decoupling network common to adjacent inverter tubes, which are always in a state of conduction opposite to the gate tubes. Current steps drawn through the decoupling networks are thereby greatly reduced. Possible oscillations, whose maximum amplitude is directly proportional to the current step, are reduced accordingly. This approach to the decoupling problem produces excellent results. It is used in several other parts of WWI, notably flip-flop circuits, in which the plates of the two tubes (one and only one of which is conducting at any time) are connected to a common decoupling network.

It is not always possible to reduce current steps by combining stages in this manner. This method is soon exhausted, leaving some feeder lines which must furnish abrupt current changes as high as 100 milliamperes or more. In WWI the number of such cases is enlarged by the great number of feeder lines necessitated by marginal checking. For these, changed design of decoupling networks is indicated. The simple addition of a resistor in parallel with the inductor of the L-C decoupling section effectively damps out oscillations. The resulting network is a good compromise between simple L-C and R-C sections.

4. ELECTROSTATIC STORAGE

4.1 TUBE PROGRAM

The storage-tube group during the last quarter was divided between production of 100-series storage tubes (ST96 model) and the development of an improved tube. Enough 100-series tubes were built for one full bank of 16 storage tubes for the initial testing of electrostatic storage in WWI. At the same time, gun studies have led to construction of a research tube capable of short-time dynamic operation with 32 × 32 arrays for the ultimate storage capacity of 1024 spots. It is too early to state how much additional work will be required to turn this marginal operation into reliable operation, but progress is encouraging.

Production of an improved-model storage tube (200-series) has started with a 50-percent increase in the scheduled rate. Work is also being done on cathode research, mosaic size effects, and further gun improvements.

4.11 Standard Tube Production

The previous Summary Report, No. 20, describes the preproduction run of storage tubes based on the ST96 specifications. These tubes are capable of storing 16 × 16 arrays with an access time of 20 to 30 microseconds. It was our original intention to terminate the preproduction run on October 1, starting at that time a production run of tubes, possibly of a new model, for use in WWI. The preproduction run, however, resulted in 13 usable tubes, and we decided to continue production of this model until a substantially improved design could be made. Because of the fair backlog of tubes already available we felt we could afford diverting some more of our effort to research tubes.

Figure 1 shows tube production in this period. Production of the standard model, hereafter called the 100-series tube because it is numbered from ST101 up, was reduced in October, largely due to the emphasis on research tubes. By November a supply of research tubes sufficient to absorb the capacity of the test group had been built, and standard tube production was stepped up to 2 a week. This rate was maintained until the last week of December, when 2 new-model tubes were built instead of the standard.

During the quarter, 18 100-series tubes were built, of which 12 proved satisfactory and 6 did not, a shrinkage of 33 percent. The average rate including October was about 1 good tube per week. If only the 7 weeks of active production are considered, the shrinkage is about 30 percent and the actual yield 1-1/2 good tubes per week.

A tabulation of the results of the entire pro-

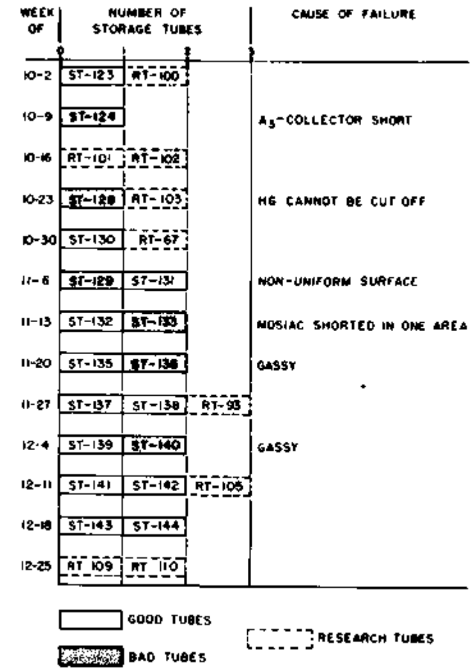


Fig. 1. Storage-tube production record.

duction run of 100-series tubes is given on page 18 (Table I). The average shrinkage was 32 percent and the average yield 1 good tube per week.

No new production difficulties were encountered during the quarter, although it became evident that some of the old troubles were not completely overcome. Of the 6 unsatisfactory tubes, 2, ST124 and ST133, had their collectors and screens touching in one area. ST128 had a holding-gun short. The storage surface of ST129 was very non-uniform under TV test conditions. It is interesting to note that this is the first evidence of a bad surface since ST108, which was built in the middle of July. The measle in ST121, mentioned in Summary Report 20, was removed, but the tube subsequently exhibited gun troubles and was again rejected. It is so listed in the tabulation. Two tubes, ST136 and ST140, proved to be gassy, a trouble which was traced to a new lot of screen material. A change in cleaning procedure for the screen corrected the difficulty.

4.12 Tube Reprocessing

The reprocessing of tubes with faulty guns or vacuums is possible. Life tests show that storage surfaces far outlive gun cathodes. Since the target assembly and body glasswork represent the major tube cost, it is economical to save these by

TABLE I

RESULTS OF PRODUCTION RUN OF 100-SERIES STORAGE TUBES

Total number of ST's built			38
Number of ST's passing static test including ST136 reprocessed			26
Number of weeks of production			25
Does not include 2 weeks of vacation or the last week of the year when 100-series production had stopped			
Average yield of passable tubes per week			1
Average Shrinkage			32%
Number of tubes not passing static test			12
Poor Surface		7	
Measles	1		
Low Capacitance spot	2		
Short to collector	2		
Non-uniform storage	2		
Poor Guns		2	
Shorted deflection plate	1		
HG cannot be cutoff	1		
Gassy		1	
1 other saved by reprocessing			
Other		2	
Processing failure	1		
A_3 - Collector short	1		
Number of ST's transferred to WW to date			15
Number of ST's not yet acceptance-tested			6
Number of ST's not passing acceptance test			5
Leaky surface		1	
Poor gun currents		4	

replacing guns when they become faulty, and then reprocessing the tubes. Both guns must be replaced since exposure to air has a bad effect on activated oxide cathodes. This technique salvages some tubes that do not pass initial tests. In general, any tube with substandard guns or poor vacuum is a candidate for reprocessing.

The two tubes reprocessed thus far were both gassy. ST114 was tried first, and the operation was successful in that the tube pumped down satisfactorily and showed good currents in the new guns. The surface still showed a bad area, however, which was originally thought due to ion bombardment when the tube was gassy.

ST136 satisfactorily passed test after reprocessing. This tube, now numbered ST136-R1, is considered acceptable for WW use, although still listed as a production failure in the production records described in 4.11.

4.13 WWI Acceptance Tests

Tubes to be used in the computer must pass the following sequence of tests:

a. Initial static test in a TV setup immediately after sealoff.

b. Possible special tests or dynamic tests.
c. A shelf life of 300 hours to check for change in characteristics including vacuum.
d. A second static test called "WWI acceptance test" to check on "c" and to certify tubes for transfer to the circuits group.
e. Installation in mount boxes and adjustment for standard currents and deflections.
f. Dynamic tests to be run in the reliability tester either before or after installation in mount boxes.

Most of the 100-series storage tubes that have passed initial tests and have not been diverted to special uses have received static acceptance tests. Good ones have been delivered to the circuits group. The test results are listed.

Passed acceptance tests	15
Rejected by acceptance test after passing initial test	5
Not acceptance-tested although passing initial test	6
Total tubes passing initial test (plus 1 reprocessed tube)	26

The "not-tested" group includes those tubes which were diverted to special uses. The 5 rejected tubes fall into the following groups:

Leaky surface	1
Poor gun currents	4

Several of these latter will be reprocessed.

4.14 The 200-Series Storage Tube

The 200-series storage tubes differ from the 100-series storage tubes in the following respects:

a. The throw (the distance between the storage surface and the final aperture of the high-velocity gun) has been reduced from the 14 inches used in the 100-series to 10 inches in the 200-series.
b. The 6-pin stem used on the target end of the early 100-series tubes has been replaced by a 10-pin stem in order to shorten the leads between the signal plate and the output coupling circuits and thus improve the r-f readout.

The 100-series and 200-series tubes are shown in Figures 2 and 3.

As discussed in Section 4.31, reduction in throw

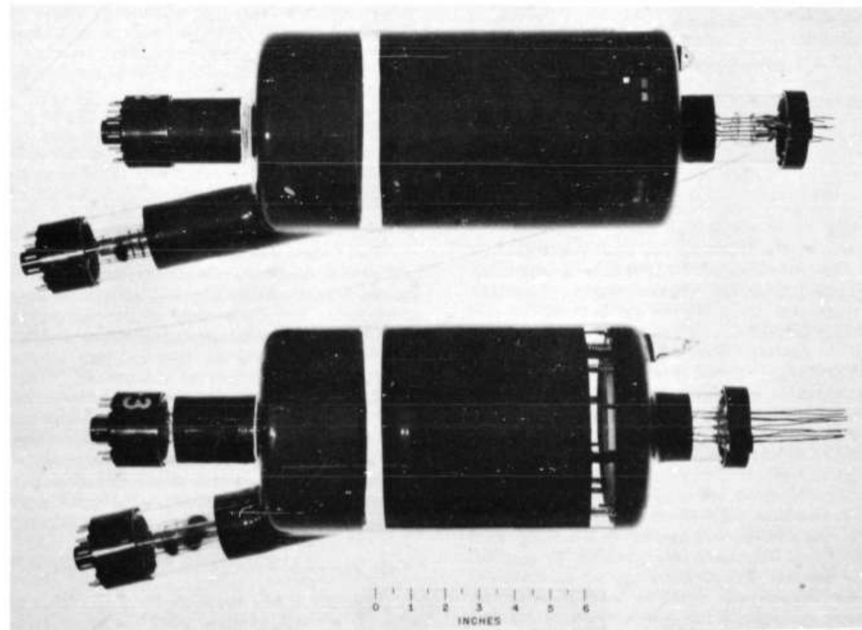


Fig. 2. Storage tubes. Above, 100-series storage tube; below, 200-series storage tube.

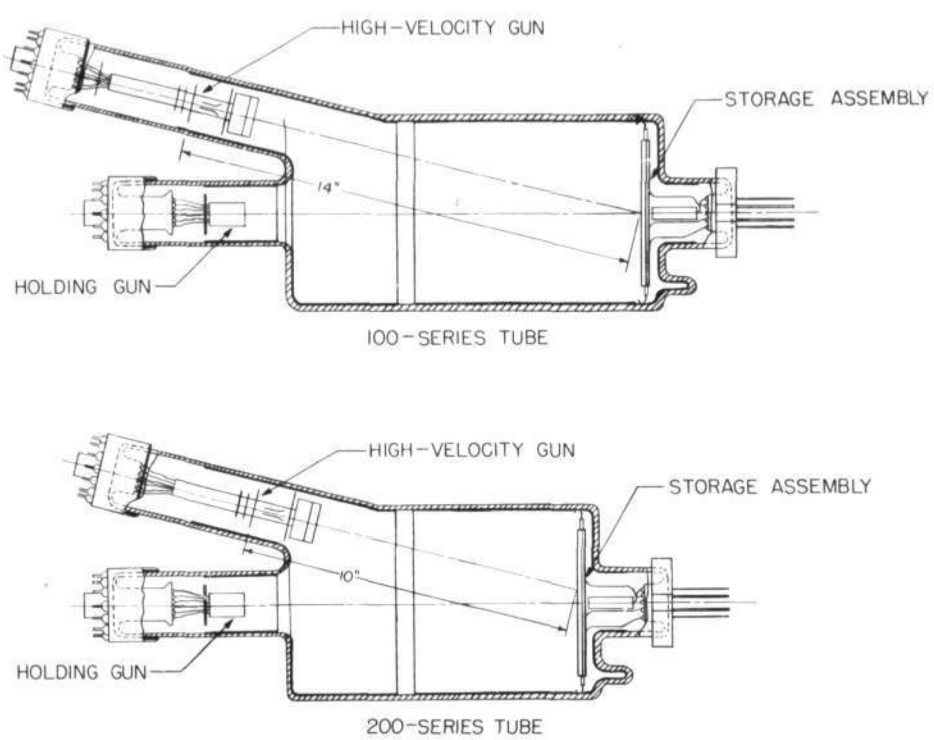


Fig. 3. Storage tubes. Above, 100-series storage tube; below, 200-series storage tube.

distance greatly improves the spot concentration of the high-velocity gun. The limits on deflection angle in the 5UP gun make 10 inches about the minimum throw that will allow the gun to cover the entire target surface. The amplitude of the readout signal is a maximum when the reading beam strikes perpendicular to the surface. The high-velocity gun should therefore be as close to the center-line of the tube as possible. The holding gun was originally placed on the tube center-line in order to provide the greatest uniformity of holding effect. Although this gun could probably be moved off the center-line to allow bringing in the high-velocity gun, the resulting tube would not fit the existing mounts. Instead, the neck for the high-velocity gun was shortened 2 inches, thus pushing the gun out into the tube and effectively reducing its distance from the center-line. The horizontal deflection plates are thus out in the body of the tube but are still out of the holding-gun beam. Tests have shown no appreciable change in the deflection-plate current pickup in 100-series and 200-series tubes.

Two inches was then taken out of the maximum body length, reducing the throw by a total of 4 inches. The resulting tube can be put in the standard mount. The neck angle of the high-velocity gun remains the same, and the holding-gun throw is reduced but 2 inches. Gun and target designs are the same for both series of tubes.

The maximum array that can be stored reliably by the 200-series tube has not yet been determined. The tube will store 32 × 32 arrays in the static tests and has done so dynamically for short periods. The tube operates with 16 × 16 arrays under the same conditions as the 100-series tube.

4.15 Future Production

Production will begin on the 200-series tube early in the next quarter, after the experimental models have been tested. We do not expect to build more of the 100-series tubes.

In addition to research tubes, scheduled

production of storage tubes may be increased from the present 2 per week to 3 per week, with an expected yield of at least 2 acceptable tubes per week. We expect to obtain increased tube output by:

a. Better construction-group efficiency from simplified procedures. An assistant will be assigned to the glass blower and some additional glass work sent to outside job shops.
b. Use of a commercial demountable evaporation system for depositing silver signal plates and perhaps beryllium mosaics. The second vacuum system, now used largely for evaporation-tube processing, would then become available for storage tubes.

When such tube simplifications as putting both guns in one neck become available, production can be further increased.

4.16 Single-Neck Tubes

It is planned to put both high-velocity and holding guns in the same neck. In the first experimental tubes this neck will be 3 to 4 inches in diameter and will be on the center-line of the tube. This change will simplify the glass work and move the high-velocity gun nearer the tube center-line. Later designs should reduce the target diameter and make the complete tube a cylinder perhaps 4 inches in diameter and 12 to 15 inches long.

The first step in putting both guns in one neck is to obtain satisfactory hard-glass stems with more pins than our present 10-pin stems. Eighteen pins should be adequate for both guns with the possible addition of deflection cutoff. The design of such a stem has started.

4.2 RELIABILITY TESTER

The reliability tester is being used for dynamic measurements on storage tubes. Tests include charging rates, spot size vs. various parameters, spot interference measurements, and the measurements of ranges of operating conditions for cycling arrays. The equipment has also been used for studying protective circuits proposed for storage tubes in WWI and for the evaluation of new tube designs.

During the next quarter the tester will be used for dynamic acceptance tests on production tubes, and for studying problems that turn up during debugging of the storage installation in the computer.

4.3 STORAGE-TUBE RESEARCH

4.31 Spot Size

The research group in the last quarter worked toward the reduction of beam diameter and the increase of current density of the high-velocity gun (SR-20). The studies have led to a substantial improvement in storage density obtained solely by shortening the tube and thus sharpening the beam.

It is known that decreasing the length of the high-velocity beam will reduce beam size and increase current density. As the target is brought closer to the gun, however, deflection angles increase, resulting in greater deflection defocusing, and the maximum angle at which the beam strikes the target is also increased, resulting in changes in secondary emission and current interception by the collector.

These effects set a limit on the minimum throw distance — already reached in the 200-series tubes — at which the entire present target diameter of 3-3/4 inches may be utilized. Reduction in target diameter must accompany further reduction in throw, which in turn will require further reduction in mosaic size (see 4.32 below) and possible changes in collector-mesh and collector-to-surface spacing. These problems continue under study.

Assuming a good vacuum in the tube (10^{-6} to 10^{-7} mm Hg), the theoretically obtainable current density in the beam is not given by cathode emission and geometric electron optics alone, but is limited to far lower values by thermal velocities and space-charge effects of the electrons. After it leaves the gun, any free-drifting electron beam can be kept convergent only up to a certain maximum distance. This distance, L, is a function of beam voltage, E, beam current, I, and the diameter, d, at which the beam passes the last aperture of the gun.

$$L = 17.5\, d\, E^{3/4}\, I^{-1/2}$$

E in kv
I in ma
L and d in the same units.

At a distance less than L, the minimum cross section of the beam is limited mainly by thermal velocities; at a distance greater than L, the beam spreads out due to its own space charge; this spreading cannot be prevented by the focusing effects (A_1 potentials) of the gun. Figure 4 shows on an exaggerated scale the measured and calculated cross sections of a beam at the maximum distance L at which it can be concentrated.

The 100-series storage tube has a beam length of 14 to 15 inches, measured from the last gun aperture to the collector surface; beam voltage, E, is 2 kv. If the beam current is limited to values less than 20 microamperes, by a negative grid bias for instance, it will be possible to concentrate the beam upon the target at a distance of 15 inches. This is the condition for which the 5UP gun was designed. However, if the beam is run at 100 microamperes, which sometimes has been attempted in the desire for higher current density, the beam cannot be concentrated beyond a throw distance of 6 inches. This means that in order to obtain concentrated spots at a current density higher than

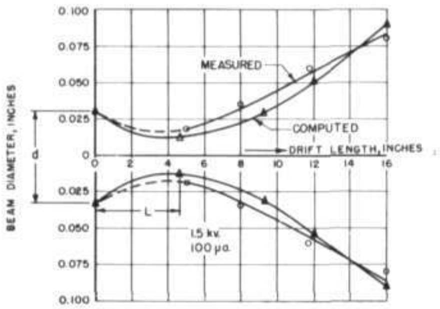


Fig. 4. Beam diameter at best focus vs. drift length.

that obtained at 20 microamperes, it is necessary to shorten the tube.

Another consideration favoring a reduction in tube size can be derived from the data presented in Fig. 5. The minimum beam diameter for a constant total beam current varies approximately linearly with beam length, but this line does not intersect the horizontal axis at the origin. Therefore, cutting the throw from 14 inches to 7 inches in the given example reduces the beam diameter to less than half.

In addition, the current density in the center of the beam (current distribution in the beam is Gaussian) varies approximately inversely with the third power of beam length within the contemplated region. This means that, keeping the same maximum current density, the beam diameter can be reduced further by grid bias. As a result, the number of spots storable on the target at this same current density rises considerably for a smaller tube, even if the target size is reduced in proportion to the reduction in beam length.

Experimental studies were carried out on specially designed research tubes to evaluate these considerations. A beam analyzer tube, RT67, shown in Fig. 6, was designed with a Faraday cage whose position could be changed so as to analyze the current distribution in the beam at distances between 5 and 15 inches from the end of the gun and at various distances from the center-line of the tube. Results of these studies are found in report E-316. When the great influence of beam length on the current density obtainable was recognized, a storage tube was built, RT93 (Fig. 7), which contained a standard but movable storage assembly to investigate storage conditions at distances between 5 and 15 inches from the gun. In this tube, at a spacing of 8 inches, a 32 × 32 array could be stored and demonstrated with television readout. Reduction of the throw to 5 inches showed further reduction of spot size in accordance with expectations. However, holding and high-velocity beams covered only a part of the surface simultaneously, which greatly limited the usefulness of that particular spacing. Experiments with RT93 are reported in M-965. Then a storage tube was built in which standard geometry was kept except that the target distance was reduced to 10 inches. Tests of this tube indicate that storage of a 32 × 32 array may be feasible with decrease in beam length the only major change in tube design.

The effect of the increase in current density on writing time has not yet been studied.

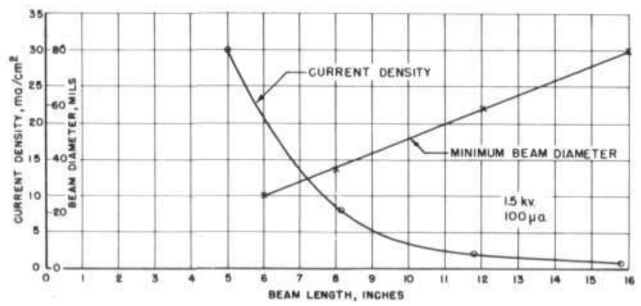


Fig. 5. Maximum current density and minimum beam diameter vs. beam length.

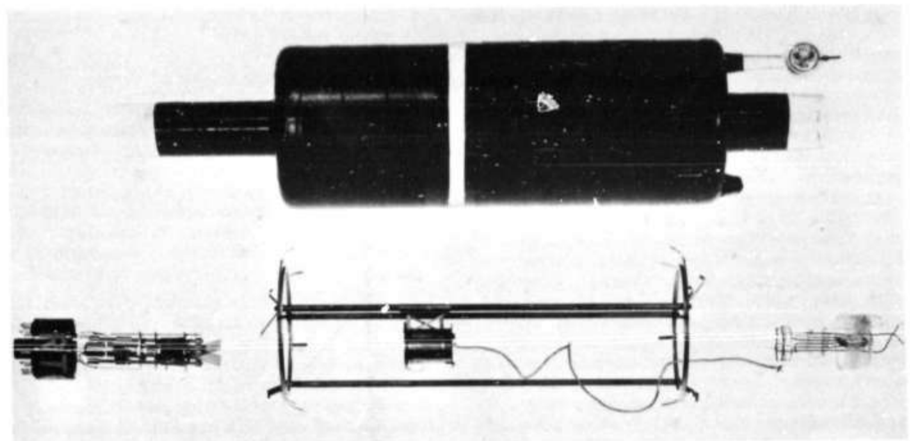


Fig. 6. Exploded view of beam analyzer tube with movable Faraday cage. An ionization gage is attached for pressure measurement.

4.32 Mosaic Size

The present production storage tubes (Summary Report 20, page 17) have surfaces with 40 mosaic squares per linear inch separated by 0.0022 inch, giving squares of about 0.023 × 0.023 inch. With a symmetrical array of 16 × 16 spots on the 3-3/4-inch storage surface, a center-to-center spot separation of 0.160 inch is available, so that 20 to 30 mosaic squares may be included within each spot. However, if a 32 × 32 array is attempted, the spot separation is reduced to 0.080 inch, and approximately 5 mosaic squares are allowed per spot. Operation of the storage tube under this condition would be decidedly marginal, since a random change in spot size of only one mosaic square would influence the readout signal by 20 to 25 percent. The use of smaller mosaic squares is dictated as one step to be taken toward increasing the storage capacity of the tubes, and an investigation of smaller mosaics is in progress.

The possible reduction in mosaic square size is limited, because each square must receive enough holding-beam current to give stable storage. Of the various factors present which oppose the stabilizing action of the holding beam, the most

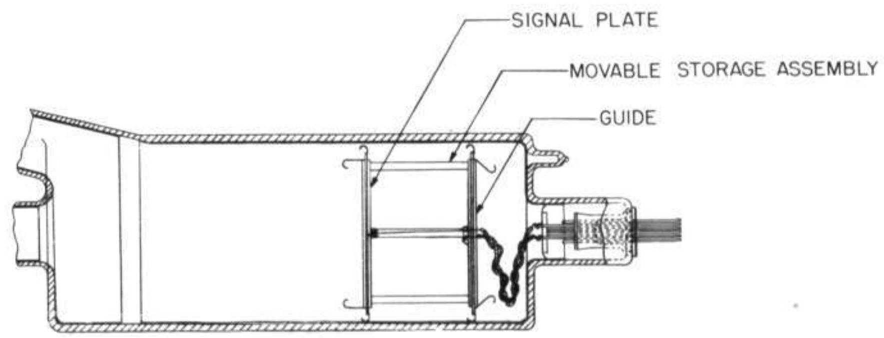


Fig. 7. Variable-throw research tube.

prominent seems to be a transient effect which occurs when positive spots are written on a negative background. When V_{HG}, the voltage between the holding-gun cathode and the collector screen (consequently, that between adjacent positive and negative mosaic squares), is set above a critical value, defined as the "maximum operating V_{HG}," the action of writing a single positive spot causes the entire surface to switch positive. The maximum operating V_{HG} decreases as the mosaic square dimensions are reduced. The "minimum operating V_{HG}," below which positive spots cannot be stored, is determined mainly by the first-crossover potential of the beryllium oxide. The mosaic square size cannot be reduced beyond the point where a usable operating range of V_{HG} exists.

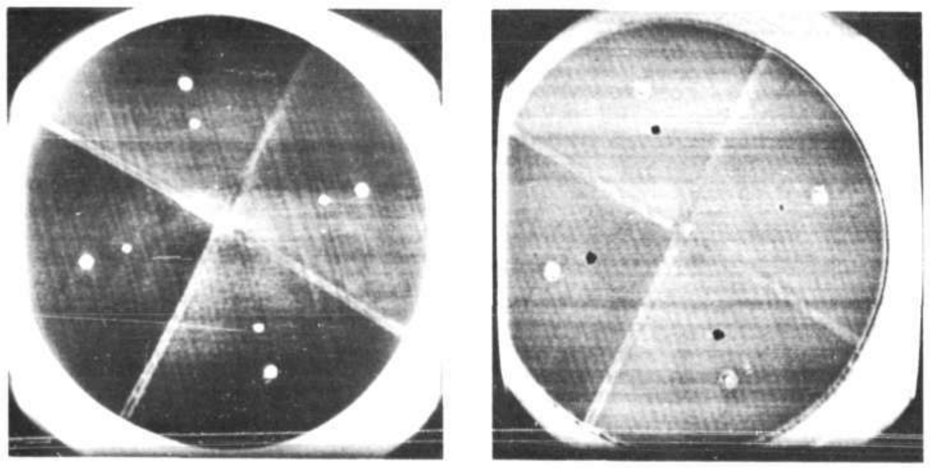
Because of the difficulties in obtaining and handling mosaic-forming screens woven of wire finer than 0.002 inch in diameter, the percentage of beryllium oxide on the surface has been reduced for the smaller mosaics tested. For example, with a wire diameter of 0.002 inch, the percentages of beryllium oxide for 40- and 100-mesh mosaics are 85 and 64, respectively. It has been observed that the 100-mesh mosaic gives a readout signal whose amplitude is about 85 percent of that obtained with the 40-mesh mosaic. This indicates that the beryllium oxide has a higher secondary emission ratio than the mica dielectric, but the slight reduction in signal level will not limit the mosaic size.

For the writing of positive spots, mosaics with smaller squares give rounder and more uniform spots, as expected. Since the conducting squares are necessarily equipotential areas, the smaller mosaics more nearly reproduce the Gaussian shape of the writing-beam current-density distribution. This effect is shown in Fig. 8a, a photograph of a television readout viewing tube. The four circular spots nearest the circumference of the surface are spacer beads 0.100 inch in diameter. The surface being examined here is that of RT62-2, which has the four following mosaic quadrants:

Quadrant Position	Mesh Squares per Inch	Square Separation Inches
Left	40	0.0022
Lower	60	0.0030
Upper	100	0.0020
Right	120	0.0025

For negative spots on a positive background, the 100- and 120-mesh mosaics exhibited unexpected variations in spot size and shape. This is particularly evident in the 120-mesh quadrant in Fig. 8b, where the write-negative charge of the high-velocity beam was constant for all four spots. This dependence of spot size upon mosaic square size is probably caused by redistribution of secondary electrons from the bombarded area of the surface, secondary electrons from the collector screen, and the effect responsible for the maximum operating V_{HG}; but it is difficult to estimate the relative importance of these effects. Fortunately, the critical aspect of writing negative is not present when a positive spot is being erased from a negative background.

During the next quarter, several research tubes will be built with complete mosaics of 60, 100, and possibly other meshes in order to verify the static study by dynamic measurement.



a. Positive spots on negative background. b. Negative spots on positive background.

Fig. 8. Television representation of 4-mosaic storage tube.

4.33 Dielectric Thickness

In the early part of the quarter, two research tubes were built with mica dielectrics of about three times the usual thickness (0.021 inch instead of 0.007 inch). It was hoped that the resulting decreased spot capacitance would result in shorter write times or in decreased current density and therefore decreased spot size with the same writing time. A thicker and therefore stiffer dielectric would also be more satisfactory mechanically. These tubes exhibited objectionable non-uniformities in their storage characteristics, and relatively little study was made of them. Considering the success obtained by gun work, it is doubtful whether any more thickness studies will be made for some time.

4.34 Storage-Tube Cathode Research

In Summary Report 20 it was pointed out that storage-tube reliability and speed may be improved by use of better, more uniform cathodes, and that cathode deterioration is the present limitation on storage-tube life. Moreover, as indicated in that report, the particular type of deterioration which is most likely to be the limiting factor on the life of storage tubes of the present production run affects the high-velocity beam current. Investigation of this phenomenon was begun late in the third quarter and has been continued in the fourth quarter. For details of the initial investigation, the reader is referred to Engineering Note E-208.

Briefly, this deterioration is manifested as an apparent partial deactivation of the cathode of the high-velocity gun during standby, that is, during periods in which heater voltage is applied to the tube but emission from the cathode of the high-velocity gun is cut off by a negative grid bias. There is a corresponding apparent reactivation of the cathode when current is again drawn after the standby period. Initially, that is for new tubes, the difference between the emission in the activated and deactivated states is insignificant, but as the tubes age the effect of standby periods on emission increases. In some cases, this effect becomes appreciable in 1000 hours of operation.

Tests have shown that the apparent deactivation of cathodes during standby is not a phenomenon

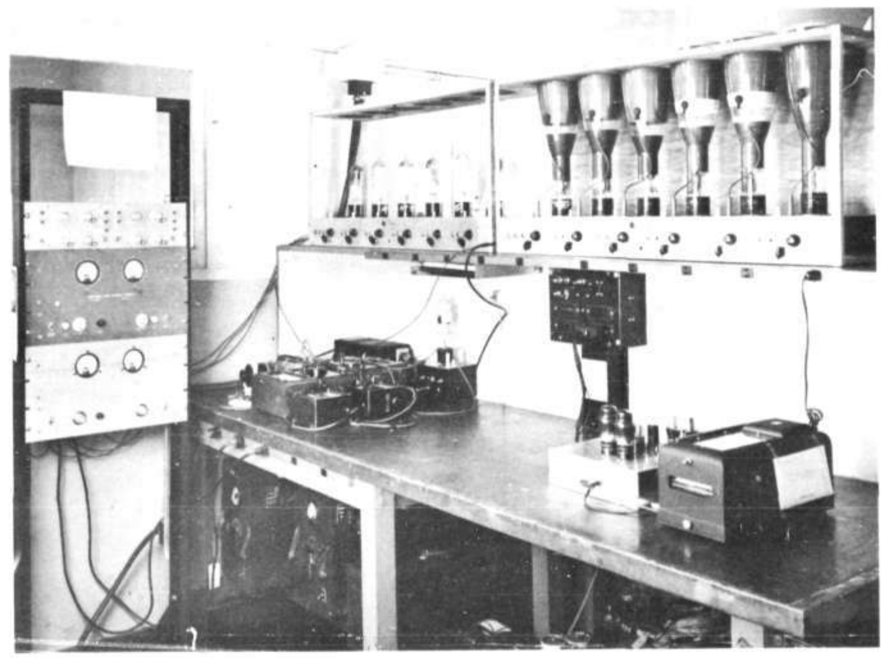


Fig. 9. Cathode study life rack.

peculiar to our storage tubes. In particular, six type 5CP1 oscillographic cathode-ray tubes (three from each of two different manufacturers) showed much the same kind of behavior as has been found in the storage-tube high-velocity guns. It appears, therefore, that the problem is a fundamental one that will require some further investigation. Figure 9 shows the equipment being used for cathode life studies.

At the beginning of this quarter we began setting up cathode-spraying facilities to produce, under closely controlled conditions, cathodes to be used both for research and for storage-tube production. Cathodes have been produced for use in research tubes since late in October. We also have sprayed cathodes for the low-velocity guns of all storage tubes produced since November 28. This period of cathode production, from the last week of October to the end of December, was used as a control period; that is, all effort was directed toward producing cathodes as nearly alike as possible. Although considerable improvement can still be made, the uniformity which has been achieved thus far is good enough to provide a basis for comparison of experimental cathodes to be produced in the next phase of this activity. During the next quarter it is planned to produce experimental cathodes having modified coating mixtures, different coating densities, and different base metals in an attempt to find the optimum cathode for our requirements.

Extension of the study of cathode deactivation under standby conditions is the subject of a master's thesis research project now in progress. This study is intended to relate the deactivation phenomenon to such factors as coating density, coating thickness, coating composition, base-metal composition, etc. Included in the study will be an investigation of the form of recovery-transient exhibited by deactivated cathodes when emission current is re-established by removal of the grid bias. Of primary interest here is the behavior of the cathodes during the first few milliseconds, since any very marked irregularity might have important bearing on the required manner of operating storage tubes in a computer.

Although the deactivation phenomenon can be minimized by proper choice of cathode coating and base metal, it does not seem likely that the effect can be entirely eliminated. As mentioned in Summary Report 20, modification of the high-velocity gun to permit drawing of continuous current from the cathode even when the beam is cut off should eliminate deactivation during standby. Unfortunately, however, any scheme which permits the continuous current to be drawn from the same area on the cathode that furnishes the controlled beam current requires some additional complication of computer circuits. On the other hand, the construction of the high-velocity gun can be modified in such a way that the continuous current is drawn from the periphery of the disk cathode. No complication of computer circuits would result from such a modification, but, since the current is drawn from a different area than that which furnishes the beam current, it is not certain that deactivation would be eliminated. Design of a simple research tube to study the effect of drawing a continuous current from the periphery of the high-velocity gun cathode while the beam current is controlled in the usual manner has been completed, and one such tube will be constructed early in January. Future investigation along this line will be governed by results obtained with the first tube.

5. INPUT - OUTPUT

5.1 INPUT-OUTPUT CONTROL

The input-output control, described in Summary Report 18, transfers numbers between the computer input-output register and the Eastman reader-recorder units (or other external memory devices).

The equipment has been constructed and installed in the computer room. The system was tested by setting up test equipment to simulate the functions of the computer and a recording unit. Approximately one month of this type of testing was required before operation was entirely satisfactory. An Eastman unit was then connected in place of the test equipment that was simulating the recorder function, the changeover being made so as to introduce the functions of the film unit one at a time.

5.2 READER-RECORDERS

The first of six film reader-recorder units was delivered to the Project on September 13. These units, developed by the Eastman Kodak Company, are designed for recording digital information on 35-mm film and for reading such recorded information from the film. They are to form a part of the input-output terminal equipment of WWI. A description of their design is given in Summary Report 13.

It was planned that the testing of these units would be divided into three phases: (1) unit testing, (2) tests with the input-output and the comparison registers and input-output control, and (3) tests with the complete WWI system. To date most of the work done on the unit that has been received has come under the first testing phase. Initially, several weeks were required for Project engineers to become familiar with the equipment. Performance of the various circuits was examined in detail, and some minor circuit changes were made to improve operation. Alignment of the optical systems was also carefully studied and some readjustments were found to be necessary as a result of changes that had occurred during shipment. Some tests were made both of the recording and of the reading functions. However, since the automatic film-processing equipment was not yet available, only short lengths of film could be prepared for these tests. As a result, only a limited amount of information was obtained as to the proper settings of the cathode-ray-tube controls for optimum film exposures.

Initial operation under the second phase of testing, in which the reader-recorder unit is connected with input-output control and its associated registers, was attempted about December 1st. This provided the first opportunity to read arbitrary numbers into the unit, and made it obvious that the phototube pick-up circuits did not respond properly to changes in pulse repetition frequency. A redesign of these circuits has been undertaken and preliminary tests of the revised circuits have been satisfactory.

Further testing of the phototube circuits will be necessary to determine the optimum design. Following that, testing phase (2) will be continued with the aim of improving the system reliability to a point where the system can be integrated with WWI with a minimum of trouble-shooting involved. Techniques for marginal checking on the film unit are to be studied as a part of this work. It is estimated that at least three months will be required to complete this phase of testing.

The second film reader-recorder is expected to be delivered in the next few weeks. Detailed testing of this unit probably will not be undertaken until the second quarter of the year.

6. MATHEMATICS, CODING, AND APPLICATIONS

6.1 DISPLAY PROGRAMS

For the past six months the complete control and arithmetic elements of WWI have been operating in a satisfactory manner, and during this time a number of problems within the capacity of the 32 registers of test storage have been set up and run. Because the storage and display facilities are incomplete, no problem has been attempted to which the solution was not previously known.

Temporary Display Equipment

A temporary display system has been set up for use in testing and demonstrating the computer until installation of the more versatile display system which is to be a part of the terminal (input and output) equipment. This system consists of a cathode-ray oscilloscope connected to a decoder with a capacity of 8 binary digits. The decoder produces a voltage with an amplitude corresponding to the sign and magnitude of a binary number, and this voltage is used to provide a vertical deflection for the scope. The horizontal deflection is provided by the saw-tooth sweep generator within the scope itself. This horizontal sweep generator controls the computer so that when the sweep starts, the computer is started; when the sweep stops, the computer is stopped, cleared, reset, and made ready to be started again by the next sweep.

Once started, the computer proceeds on its own. Whenever a value to be plotted has been obtained, a special instruction in the program puts the new value into the decoder (thus setting the vertical deflection) and intensifies the scope beam momentarily, thus plotting a spot on the scope face. Since the time required by the computer to obtain each new value is about constant and since the scope sweep is approximately linear, the horizontal distance between spots on the scope face is nearly constant. The frequency of the horizontal sweep is adjusted so that the length of each sweep corresponds to the time required by the computer for the solution of the problem at hand. The display system is further discussed in Section 5.2 of Summary Report 20.

Test Storage

The storage of the computer (i.e., the capacity of the machine to accept and remember numbers and instructions) is at present restricted to the 32 test-storage registers, each 16 binary digits long. Of these 32 storage registers, 5 are composed of flip-flops and are therefore erasable and may be used for storing new information obtained by the computer during automatic operation. These flip-flop (FF) storage registers can each be reset to a quantity determined by an associated set of toggle switches, the reset occurring if desired at the end of each cycle of the program and/or the end of each sweep of the scope. The remaining 27 registers are composed of toggle switches which must be individually set by hand and cannot be erased or altered by the computer in automatic operation. All numbers and all instructions are stored in these 32 storage registers.

6.11 Solution of Second Order Differential Equations

6.111 Homogeneous Equations

As a demonstration of computer operation, Display Program No. II has been written for the numerical solution of a homogeneous second order linear differential equation with constant coefficients. (Display Program No. I, values of the powers of x, was described in Summary Report 20.) This equation,

$$A \frac{d^2e}{dt^2} + B \frac{de}{dt} + Ce = 0 ,$$

describes an oscillating system with viscous damping, such as a series circuit with an inductance, capacitance, and resistance. Because the program must be confined to the 32 registers of test storage, a rather crude first order extrapolation and integration method is used.

Let

$$A = 1$$

$$B = 2\zeta\omega$$

$$C = \omega^2$$

(These quantities are so chosen because ζ is then the damping ratio and ω is the natural frequency of oscillation.)

The equation becomes

$$\frac{d^2e}{dt^2} + 2\zeta\omega \frac{de}{dt} + \omega^2 e = 0 ,$$

which can be written as two first order equations (the first equation is simply a chosen substitution; the second is obtained by making the substitution in the original equation).

$$\frac{de}{dt} = \omega v$$

$$\frac{dv}{dt} = - \omega(2\zeta v + e).$$

A numerical formula (actually a difference equation which approximates the differential equation) can then be obtained (cf: E-304 — Display Program Number II):

$$v_{n+1} = v_n - \omega h \left\{ e_n + (2\zeta + \frac{1}{2}\omega h)\left[v_n - \frac{1}{2}\omega h (2\zeta v_n + e_n) \right] \right\}$$

$$e_{n+1} = e_n + \omega h \left[\frac{v_n + v_{n+1}}{2} \right]$$

where

$e_n = e(nh)$ = the value of e when $t = nh$, where n is an integer and h is some arbitrarily chosen constant increment in time.

$v_n = v(nh)$

The above equations permit calculation of v_{n+1} and e_{n+1} from the values of v_n and e_n and the constants ζ, ω, and h. This process of obtaining a new point from a past point can be continued indefinitely. Display Program No. II directs the computer to evaluate v_{n+1} and e_{n+1} assuming v_n and e_n have already been obtained. The program simply repeats at a rate of about 3000 cycles per second, each cycle yielding one new value of e and of v.

It is important to notice that the frequency ω (in radians per second) and the increment h (in seconds per point) always appear in the combination ωh, never separately. This product ωh is expressed in radians per point, and $2\pi/\omega h$ is then the number of points per period. With an increase in the value of ωh, fewer points per period are produced. This may be thought of as increasing ω with h fixed or as increasing h with ω fixed; both have the same effect and are inseparable.

The exact solution of the difference equation used here is the product of a sine wave times an exponential. When the damping ratio is zero, this exponential is always positive, regardless of how close together the points are taken, i.e., regardless of how small a value is chosen for h (Report R-114, A Numerical Integration Method, W. S. Loud). Thus, for $\zeta = 0$, the numerical solution (using the difference equation) should diverge exponentially from the true sinusoidal solution of the differential equation. However, when about 30 or more points are taken per period ($\omega h < 0.25$) the solution computed by WWI diverges only slightly (periodically) from the true solution, even when the computer runs free and extrapolates the solution through thousands of periods of the sine wave. The reason for this is that with such small values of ωh, the roundoff error masks the truncation error almost completely. The periodic behavior is attributed to the roundoff error.

6.112 Non-Homogeneous Equations

In order to make a more interesting display than can be obtained from the homogeneous equation, which simply displays the decay of energy in an initially disturbed oscillatory system, a program (Display Program No. IV) was written which introduces a driving function E(t) into the equation

$$\frac{d^2e}{dt^2} + 2\zeta\omega \frac{de}{dt} + \omega^2 e = \omega^2 E(t) .$$

In order to fit a program for the solution of this more elaborate problem into the 32 test-storage registers, some simplification had to be made in the numerical method. First, slightly simpler and less accurate first order approximation formulas were derived. Second, the quantity ωh was incorporated into the program as an integral power of 2, so that ωh cannot be varied as smoothly or easily as when it was stored explicitly as a separate adjustable constant. With these two modifications the solution was programmed in 23 registers, leaving 9 registers, including one FF register, available for a function-generating program. The formulas used were (cf: E-320, Display Program No. IV):

$$v_{n+1} = v_n + \omega h \left[(1 - \omega h\zeta)(E_n - 2\zeta v_n - e_n) - \frac{1}{2}\omega h\, v_n \right]$$

$$e_{n+1} = e_n + \omega h \left[\frac{v_n + v_{n+1}}{2} \right]$$

The program plots both the driving function E(t) and the response e(t), obtaining one value of each in one cycle of the program. As before, the program is repeated about 3000 times per second.

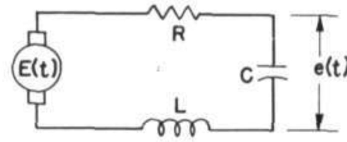
In the non-homogeneous case, the formulas used are a poorer approximation than those used in the homogeneous case; consequently, the numerical solution for $E(t) = \zeta = 0$ does grow exponentially. With $\omega h = 0.25$, however, quite satisfactory results are obtained for at least the first few periods of solution. Photographs of a few of these results are shown on page 30.

6.12 Target-Seeking Simulation

Among important applications of the Whirlwind computer are studies of (1) control of physical systems, such as air traffic, military operations, or chemical processes, (2) simulation of physical systems for purposes of experiment, design study, and instruction, and (3) mathematical problems which involve a great many operations to obtain a few results, such as boundary value problems which are solved by numerical cut-and-try procedures or large algebraic systems solved by successive approximation.

To illustrate the simulation aspect, a display program (cf: E-314, Display Program No. III) was written which pictorially illustrates, after a fashion, the control and the mathematical cut-and-try aspects as well. The computer is directed by the program to plot two things on the display scope: (1) a horizontal line whose left end can be shifted

WHIRLWIND I DISPLAY
OF TYPICAL DRIVING FUNCTIONS AND RESPONSES

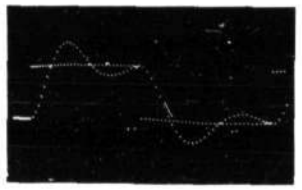


$$\frac{d^2e}{dt^2} + 2Z\omega\frac{de}{dt} + \omega^2 e = \omega^2 E(t)$$

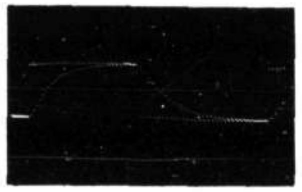
$Z = \frac{R}{2}\sqrt{\frac{C}{L}}$ = DAMPING RATIO $\qquad \omega = \frac{1}{\sqrt{LC}}$ = FREQUENCY

h = INTERVAL BETWEEN POINTS

PLOTS OF E(t) AND e(t) AGAINST TIME
CALCULATED USING DISPLAY PROGRAM NUMBER IV



E(t) = SQUARE WAVE
$Z = \frac{1}{4}$ $\quad \omega h = \frac{1}{4}$



E(t) = SQUARE WAVE
$Z = 1.0$ $\quad \omega h = \frac{1}{4}$

E(t) = STEP FUNCTION
$Z = \frac{1}{8}$ $\quad \omega h = \frac{1}{4}$

E(t) = SAWTOOTH WAVE
$Z = 1.0$ $\quad \omega h = \frac{1}{4}$

right or left by changing toggle switches and (2) a section of a vertical parabola, starting at the left end of the sweep with an initial slope which can be varied by the computer. If the left end of the line is imagined to be a target and the parabola is imagined to be the trajectory of a shell, the various possible configurations can be interpreted as undershooting, on target, or overshooting.

undershooting on target overshooting

The program then instructs the computer to measure the error (or distance by which the shell misses the target), to make a change in the initial slope of the parabola in accordance with the error, to plot the new trajectory, measure the new error, and so on. Thus the program directs the computer to simulate a control device which works by a cut-and-try method. The demonstration of simulation is made more realistic by arranging the cut-and-try (or error feedback) so that the initial slope of the parabola is changed with a constant acceleration. Thus if the display initially shows an on-target situation and the target is then suddenly shifted to the right by throwing a switch, the parabola begins gradually to grow, picking up speed until it nears the target. It then slows down and settles on the target. By appropriate changes in the program, the characteristics of the simulated system can be varied so that the rate of searching and the amount of hunting can be independently increased or decreased.

6.2 STORAGE OF PULSE-CODED INFORMATION

An application for the Whirlwind storage tube in a device other than a digital computer is described in a recent MIT master's thesis by A. J. Lephakis done in the Research Laboratory of Electronics. In laboratory investigations of certain basic communication problems, there is need for a binary information-storage system. Such a storage system should be as flexible as possible; the system should store both periodic and non-periodic pulses; it should provide both compression and expansion of the time scale of a group of pulses; and it should be capable of accepting new pulses while stored pulses are being taken out. The project described in this thesis consisted of the selection, design, and construction of a storage system suitable for general-purpose laboratory use.

The properties of possible storage systems employing suitable existing storage devices were investigated. Flip-flop storage systems are highly flexible, but require an excessively large quantity of equipment. The flexibility of storage systems utilizing ultrasonic-line storage loops is limited by the synchronization required between the standard clock pulses and the input and output pulses. The uses of storage systems employing magnetic recording media are restricted by limitations in the associated mechanical equipment. The investigation showed that the most flexible, and yet practical, general-purpose storage system which can be devised from existing storage devices is an electrostatic-storage-tube system employing Whirlwind tubes. Design of the experimental system has been completed, and most of the component units have been constructed and are operating satisfactorily.

The experimental storage system employs two storage channels, each of which consists of a storage tube and the circuits required to operate the tube; new pulses are stored in one channel while stored pulses are being recovered from the other. The auxiliary circuits used in each storage channel are two deflection units, which generate the discrete-spot deflection pattern; a gate-generator unit, which generates the gates applied to the storage-tube electrodes during writing and reading; and a reading unit, which contains the radio-frequency reading circuits. The control unit switches the writing and reading operations from one storage channel to the other. Provisions have been made in the equipment to test the operation of the storage system.

The storage sy..tem contains two storage tubes, two cathode-ray monitor tubes, and approximately 300 vacuum tubes. Four relay racks will be occupied by this equipment and the power supplies which operate it. Each of the storage tubes will store 256 pulses. It is expected, however, that tubes having a capacity of 1024 pulses will be available in the future; the storage-system equipment was designed to accommodate such tubes.

6.3 A SHORT GUIDE TO CODING
(Using the Whirlwind I code of October 1949)

COMPUTER PROGRAMS

Program. A program is a sequence of actions by which a computer handles a problem. The process of determining the sequence of actions is known as programming.

Flow diagrams. A flow diagram is a series of statements of what the computer has to do at various stages in a program. Lines of flow indicate how the computer passes from one stage of the program to another.

Coded program. Programs and flow diagrams are largely independent of computer characteristics, but instructions for a computer must be expressed in terms of a code. A set of instructions that will enable a computer to execute a program is *called a coded program, and the process* of preparing a coded program is known as coding.

Orders and operations. Individual coded instructions are known as orders and call for specific operations such as multiply, add, shift, etc.

The computer code. The computer code described here is that of Whirlwind I, an experimental computer using binary digits, single-address order code, parallel operation, and electrostatic storage. It is expected that computers of this type will ultimately achieve an average speed of 50,000 operations per second.

COMPUTER COMPONENTS

Registers and words. A register has 16 digit positions each able to store a one or a zero. A word is a set of 16 digits that may be stored in a register. A word can represent an order or a number.

Arithmetic element. Arithmetic operations take place in the arithmetic element, whose main components are three flip-flop registers, the *A-register, the* accumulator, and *the* B-register (AR, AC, BR). The 16 digit positions of AR starting from the left are denoted by AR 0, AR 1, . . ., AR 15. Similarly for AC, BR. Words enter AC through AR; BR is an extension of AC.

Storage. The term "register" by itself refers to the main electrostatic storage, which consists of 2^{11} or 2048 registers, each of which is identified by an address. These addresses are [illegible]-digit binary numbers from 0 to 2047. The computer identifies a register by its address.

Input-output. All information entering or leaving the computer is temporarily stored in the input-output register (IOR). The computer regulates the flow of information between the internal storage and IOR, and also calls for any necessary manipulation of external units. The descriptive names of the input-output orders were chosen for photographic film reader-recorder units, but the orders are applicable to other types of external equipment.

Control element. The control element controls the sequence of computer operations and their execution. Instructions are obtained from storage *in the form* of individual orders, each of which is represented by a single word.

Inter-connections. The four main elements (storage, control, arithmetic, and input-output) are connected by a parallel communications system, known as the bus.

REPRESENTATION OF ORDERS

Operation section. When a word is used to represent an order the first (left-hand) 5 digits, or operation section, specify a particular operation in accordance with the order code.

Address section. The remaining 11 digits, or address section, are interpreted as a number with the binary point at the right-hand end. In the majority of orders this number is the address of the register whose contents will be used in the operation. In orders sl, sr, the number specifies the extent of a shift; in rf, rb, the number specifies an external unit; in ri, rs, the address section is not used.

Example. The order ca x has the effect of clearing AC (making all the digits zero) and then putting into AC the word that is in the register whose address is x. If q is a quantity in some register, the order needed to put q in AC is not ca q but ca x, where x is the address of the register that contains q.

REPRESENTATION OF NUMBERS

Single-word representations. When a word is used to represent a number the first digit indicates the sign and the remaining 15 are numerical digits. For a positive number the sign digit is zero, and the 15 numerical digits with a binary point at their left specify the magnitude of the number. *The negative* -y of a positive number y is represented by complementing all the digits, including the sign digit, that would represent y. (The complement is formed by replacing every zero by a one and every one by a zero.) In this way a word can represent any multiple of 2^{-15} from $2^{-15} - 1$ to $1 - 2^{-15}$. Neither +1 nor -1 can be represented by a single word. Zero has two representations, either 16 zeros or 16 ones, which *are called +0 and -0 respectively.*

Overflow — increase of range and accuracy. With single-word representation the range is limited to numbers between $2^{-15} - 1$ and $1 - 2^{-15}$. Programs must be so planned that arithmetic operations will not cause an overflow beyond this range. The range may be extended by using a scale factor, which must be separately stored. Accuracy can be increased by using two words to represent a 30-digit number.

COMPUTER PROCEDURE

Sequence of operations. After the execution of an order the program counter in the control element holds the address of the register from which the next order is to be taken. Control calls for this order and carries out *the* specified operation. If the order is not sp or cp(-) the address in the program counter then increases by one so that the next order is taken from the next consecutive register. The sp and cp(-) orders permit a change in this sequential procedure.

Transfers. A transfer of a digit from one digit position to another affects only the latter digit position, whose previous content is lost.

Negative zero. The subtraction of equal numbers produces a negative zero in AC, except when AC contains +0, and -0 is subtracted from it.

Manipulation of orders. Words representing orders may be handled in the arithmetic element as numbers.

Procedure in the arithmetic element. *The execution of an addition in*cludes the process of adding in carries; this process treats all 16 digits as if they were numerical digits, a carry from AC 0 being added into AC 15. A subtraction is executed by adding the complement. Multiplication, division, shifting and round-off are all executed with positive numbers, complementing being performed before and after the process when necessary. For round-off the digit in BR 0 is added into AC 15.

NOTATION FOR CODING

Addresses. A coded program requires certain registers to be used for specified purposes. The addresses of these registers must be chosen before the program can be put into a computer, but for study purposes this final choice is unnecessary, and the addresses can be indicated by a system of symbols or index numbers.

Writing a coded program. Registers from which control obtains orders may be called action registers, and should be listed separately from registers containing other information, which may be called data registers. A coded program is written out in two columns; the first contains the index number of each action or data *register, and the second column* indicates the word that is initially stored in that register. In many cases part or all of a word may be immaterial because the contents of the register in question will be changed during the course of the program. This state of affairs is indicated by two dashes, for example, ca --.

The abbreviations RC, CR. Abbreviations used in referring to the *register that* contains a certain word or to the word in a certain register are

RC . . . = (Address of) Register Containing . . .
CR . . . = Contents of Register (whose address is) . . .

The symbol ri x. When an address forms part of an order it is represented by the last 11 *digits of a word whose first* 5 digits specify an operation. An address x that is not part of an order is represented by the last 11 digits of a word whose first 5 digits are zero, which is equivalent to specifying the operation ri. Thus the word for an unattached address x may be written ri x. It could also be written $x \times 2^{-15}$.

AC = Accumulator   AR = A-Register   BR = B-Register

x is the address of a storage register; n is a positive integer; k designates an external unit

Order	Operation: Name	Code: Decimal	Code: Binary	Function
ri --	read initially	0	00000	Take words from external unit until internal storage is full.
rs --	remote unit stop	1	00001	Stop external unit.
rf k	run forward	2	00010	Prepare to use external unit k in forward direction.
rb k	run backward	3	00011	Prepare to use external unit k in backward direction.
rd x	read	4	00100	Transfer to register x a word supplied by external unit.
rc x	record	5	00101	Arrange for transfer of contents of register x to external unit.
ts x	transfer to storage	8	01000	Transfer contents of AC to register x.
td x	transfer digits	9	01001	Transfer last 11 digits from AC to last 11 digit positions of register x.
ta x	transfer address	10	01010	Transfer last 11 digits from AR to last 11 digit positions of register x.
cp(-)x	conditional program	14	01110	If number in AC is negative, proceed as in sp; if number is positive disregard the cp(-) order, but clear the AR.
sp x	subprogram	15	01111	Take next order from register x. If the sp order was at address y, store y + 1 in last 11 digit positions of AR.
ca x	clear and add	16	10000	Clear AC and BR, then put contents of register x into AC. If necessary, add in carry from previous sa addition.
cs x	clear and subtract	17	10001	Clear AC and BR, then put complement of contents of register x into AC. If necessary, add in carry from previous sa addition.
ad x	add	18	10010	Add contents of register x to contents of AC, storing result in AC.
su x	subtract	19	10011	Subtract contents of register x from contents of AC, storing result in AC.
cm x	clear and add magnitude	20	10100	Clear AC and BR, then put positive magnitude of contents of register x into AC. If necessary add in carry from previous sa addition.
sa x	special add	21	10101	Add contents of register x to contents of AC, storing result in AC and retaining any overflow for next ca, cs, or cm order. Only orders 1 through 15 may be used between the sa order and ca, cs, or cm orders for which the sa is a preparation.
ao x	add one	22	10110	Add the number 1×2^{-15} to the contents of register x. Store result in AC and in register x.
mr x	multiply and round off	24	11000	Multiply contents of register x by contents of AC; round off result to 15 numerical digits and store in AC. Clear BR.
mh x	multiply and hold	25	11001	Multiply contents of register x by contents of AC and retain the full product in AC and the first 15 digit positions of BR, the last digit position of BR being cleared.
dv x	divide	26	11010	Divide contents of AC by contents of register x, leaving 16 numerical digits of the quotient in BR and ±0 in AC according to sign of the quotient. (The order sl 15 following the dv order will round off the quotient to 15 numerical digits and store it in AC.)
sl n	shift left	27	11011	Multiply the number represented by the contents of AC and BR by 2^{n}. Round off the result to 15 numerical digits and store it in AC. Disregard overflow caused by the multiplication, but not that caused by round-off. Clear BR.
sr n	shift right	28	11100	Multiply the number represented by the contents of AC and BR by 2^{-n}. Round off the result to 15 numerical digits and store it in AC. Clear BR.
sf x	scale factor	29	11101	Multiply the number represented by the contents of AC and BR by 2 sufficiently often to make the positive magnitude of the product equal to or greater than 1/2. Leave the final product in AC and BR. Store the number of multiplications as last 11 digits of register x, the first 5 digits being undisturbed.

NOTES ON THE ORDER CODE

Effect of operations. The functions of the various orders are described above. It is to be assumed that AR, AC, BR, and the register whose address is x are undisturbed unless the contrary is stated.

AR. AR is primarily a buffer register for passing words into AC. After orders ca x, cs x, ad x, su x, sa x, and ao x it contains the number originally contained in register x. After orders cm x, mr x, mh x, and dv x it contains the magnitude of the contents of x. The effect of sp x and cp(-)x is stated above. No other order changes the contents of AR.

BR. A number stored in BR always appears as a positive magnitude, the sign of the number being assumed to be that indicated by the sign digit in AC. This convention has no effect on the logical result of the operations involving BR except that when BR contains a number that will be used later it is necessary to retain the appropriate sign digit.

Alarms. If the result of an arithmetic operation exceeds the register capacity (i.e., if overflow occurs), a suitable alarm is given except as mentioned in connection with orders sa x and sl n.

Shift orders. A multiplication overflow in sl is lost without giving an alarm, but an overflow from round-off gives an alarm. Orders sr 0 and sl 0 only cause round-off, an alarm being given if an overflow occurs. The integer n is treated modulo 32, i.e., sl 32 = sl 0, sl 33 = sl 1, etc.

Scale factors. If all the digits in BR are zero and AC contains ±0, the order sf x leaves AC and BR undisturbed and stores the number 33 in the last 11 digit positions of register x.

Division. Let u and v be the numbers in AC and register x when the order dv x is used. If $|u| < |v|$ the correct quotient is obtained and no overflow can arise. If $|u| > |v|$ overflow occurs and gives an alarm. If $u = v \neq 0$ the dv order leaves 16 ones in BR and round-off in a subsequent sl 15 would cause overflow and give an alarm. If $u = v = 0$ a zero quotient is obtained.

7. APPENDIX

7.1 VISITORS

During the past quarter the Laboratory has had among its visitors the following:

Dr. C. V. L. Smith, Head, Computer Branch, Office of Naval Research.

Dr. Howard Aiken, Dr. Benjamin L. Moore, and Dr. Way Dong Woo of the Computation Laboratory, Harvard University.

Mr. M. K. Goldstein of the Air Navigation Development Board.

Dr. S. N. Alexander of the National Bureau of Standards and Dr. F. R. Darne of the Bureau of Ships, who discussed storage tubes.

Capt. D. P. Tucker and Mr. Charles L. Stec of the Electronics Design and Development Division of the Bureau of Ships, with Capt. H. R. Taylor of the Material Inspection Service.

Mr. John T. Parsons, Mr. Frank L. Stulen, Mr. R. B. Parker, and Mr. Elmer A. Burdg of the Parsons Corporation and Mr. Leo P. Gajda of the Snyder Tool Company, to discuss applications of digital techniques to problems of automatically-controlled milling.

Mr. T. V. Moore of the Standard Oil Development Company, who was interested in problems of oil reservoirs.

Mr. E. C. DuFort and Mr. Louis B. Horwitz of the Continental Oil Company, to consider possible ways of using digital computation in various phases of the oil industry.

Mr. Ralph D. Bennett of the Naval Ordnance Laboratory.

Mr. Joseph Kelar of Engineering Research Associates, interested in electrostatic storage.

Mr. C. L. Estes and Mr. L. Feit of Federal Telecommunications Laboratories, who spent some time familiarizing themselves with the computer system and its circuits.

Mr. S. L. Coulson of the Bureau of Ordnance and Mr. B. G. H. Rowley, Mr. R. Stuart Williams, Lt. A. R. Clark, Mr. H. A. Pout, Mr. N. D. Hill, and Mr. R. A. Head of the British Joint Services Mission.

Dr. H. Buckingham, Head of the Electrical Engineering Department of The College of Technology, Bradford, England.

7.2 REPORTS AND PUBLICATIONS

Project Whirlwind technical reports and memorandums are routinely distributed to only a restricted group who are known to have a particular interest in the Project. Other people who need information on specific phases of the work may obtain copies of individual reports by making specific requests to John C. Proctor, Servomechanisms Laboratory, 211 Massachusetts Avenue, Cambridge 39, Massachusetts.

The following reports and memorandums were among those issued during the fourth quarter of 1949:

No.	Title	No. of Pages	Date	Author
R-172	The Study of Non-Linear Servomechanisms with the Aid of an Automatic Digital Computer (SM Thesis, Abstract in E-311)	164	9-26-49	J. E. Pierson
	A Short Guide to Coding, Using the Whirlwind I Code of October, 1949.	2		
E-202	Coupling Circuits for a Storage-Tube Output System (Abstract SM Thesis)	2	11-9-49	C. H. R. Campling
E-256-1	Washing Procedures for Storage Tube Parts — Series W	17	10-17-49	T. R. Parkins A. F. Greenlaw
E-289	Gun Driver	4	9-2-49	G. G. Hoberg
E-290	A Built-In Monitor System for WWI Electrostatic Storage Circuits	7	9-2-49	G. G. Hoberg
E-295	Test Program No. I, Computer Complementing	3	10-17-49	C. W. Adams
E-296	Test Program No. II, Operation Matrix Check	4	10-13-49	C. W. Adams
E-297	Test Program No. III, Counting in AC	3	10-13-49	C. W. Adams
E-298	Test Program No. IV, Shifting in AC	3	10-13-49	C. W. Adams
E-299	Test Program No. V, Binary to Decimal Conversion and Reconversion	8	10-28-49	C. W. Adams
E-300	Display Program No. I: Family of Parabolas and Powers of X	3	10-17-49	G. Cooper
E-301	Notes on Making Tungsten Springs	2	9-28-49	I. Paulsen
E-302	Storage Tube Deflection Pattern	4	10-5-49	C. W. Adams
E-303	Voltage Calibrator	3	9-9-49	H. Kenosian R. Rathbone
E-304	Display Program No. II: Second Order Differential Equation	6	10-25-49	G. Cooper
E-306	Basing Procedure	5	10-21-49	R. B. Angus
E-307	Development of Storage Tube Circuits	10	10-27-49	S. H. Dodd
E-308	Temporary Deactivation of Storage Tube Cathodes under Stand-By Conditions	4	10-31-49	H. Klemperer
E-310	Automatic Control Box for TV Demonstrator	2	10-31-49	A. H. Ballard
E-312-1	Calibration of Vacuum Measurements in Storage Tubes	3	12-9-49	H. E. Rowe
E-313	Temperatory Operation qs — Switch Check and Test Program No. VI — Switch Check	4	12-2-49	C. W. Adams
E-314	Display Program No. III: Target Seeking Simulation	10	12-8-49	C. W. Adams

No.	Title	No. of Pages	Date	Author
M-896	MS Thesis Research Proposal; Pulse Response and Testing of Wideband Coupling Networks	13	9-1-49	R. L. Massard
M-901	Data on Electron Gun Currents in Electrostatic Storage Tubes	2	9-22-49	M. Florencourt
M-909	Operation of Electrostatic Storage During Test Storage Orders	4	10-20-49	R. P. Mayer
M-910	Reading Test Storage to Bus Via Program Register	3	10-21-49	R. P. Mayer
M-911	Temporary Use of A-Register in Place of Program Register	3	10-21-49	R. P. Mayer
M-913	Conference on Vacuum-Tube Problems at Sylvania - Emporium	3	10-20-49	E. S. Rich
M-915	Cycling of Power in Turning on Storage Tubes	2	10-26-49	S. H. Dodd
M-922	Vacuum Tube Failures During August, 1949	2	11-1-49	H. B. Frost
M-923	Vacuum Tube Failures During September, 1949	1	11-2-49	H. B. Frost
M-925	Vacuum Tube Failures During October, 1949	2	11-4-49	H. B. Frost
M-926	Notes on "High Precision Measurements With Simple Optical Equipment"	2	11-8-49	R. Shaw
M-927	Grid-Cathode Shorts in Storage Tubes	3	11-9-49	J. O. Ely
M-930	Proposed "Inactivity Alarm" Circuit	2	11-25-49	C. W. Adams
M-948	Vacuum Tube Failures During November, 1949	3	12-2-49	H. B. Frost
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